REPORT DOCUMENTATION PAGE	Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
13-02-2018	Final Report	1-Aug-2015 - 31-Jul-2017

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
Final Report: Stretchable Capacitors that Electrically Luminesce, Sense, and Actuate for Biomimetic Coloration	W911NF-15-1-0464
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER 111111
6. AUTHORS	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES	8. PERFORMING ORGANIZATION REPORT NUMBER
Cornell University Office of Sponsored Programs 373 Pine Tree Road Ithaca, NY 14850 -2820	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES)	10. SPONSOR/MONITOR'S ACRONYM(S) ARO
U.S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211	11. SPONSOR/MONITOR'S REPORT NUMBER(S) 67528-EG.11

12. DISTRIBUTION AVAILIBILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Robert Shepherd
UU	UU	UU	UU		19b. TELEPHONE NUMBER 607-255-8654

Standard Form 298 (Rev 8/98)
Prescribed by ANSI Std. Z39.18

RPPR Final Report
as of 15-Feb-2018

Agency Code:

Proposal Number: 67528EG **Agreement Number: W911NF-15-1-0464**

INVESTIGATOR(S):

Name: Robert F. Shepherd
Email: rfs247@cornell.edu
Phone Number: 6072558654
Principal: Y

Organization: **Cornell University**
Address: Office of Sponsored Programs, Ithaca, NY 148502820
Country: USA
DUNS Number: 872612445 EIN: 150532082

Report Date: 31-Oct-2017 Date Received: 13-Feb-2018
Final Report for Period Beginning 01-Aug-2015 and Ending 31-Jul-2017
Title: Stretchable Capacitors that Electrically Luminesce, Sense, and Actuate for Biomimetic Coloration
Begin Performance Period: 01-Aug-2015 **End Performance Period:** 31-Jul-2017
Report Term: 0-Other
Submitted By: Robert Shepherd Email: rfs247@cornell.edu
Phone: (607) 255-8654
Distribution Statement: 1-Approved for public release; distribution is unlimited.

STEM Degrees: 2 **STEM Participants:** 10

Major Goals: This proposal is about enabling methods to better understand visual perception as it pertains to dynamic camouflage. Cephalopod's (e.g., octopuses and cuttlefish) make themselves invisible to extremely sophisticated visual predation using dynamic camouflage. Despite their remarkable abilities, these animals use only three types of coloration patterns: Uniform, Mottled, and Disruptive. Overlaid on this color camouflage are many other disguise techniques; the cuttlefish, for example, also uses pattern generation, skin texture, and body posture to disguise or reveal themselves. Though some basic explanations of how these animals perform these maneuvers and when they choose to implement them has recently been explained, true understanding of how to control and use dynamic camouflage in a human context will only be revealed using synthetic systems, instead of animal models. The goal of this proposal is to develop synthetic chromatophores that display color electrically. To create stretchable synthetic chromatophores, we synthesized high density arrays of individually addressable elastomeric light emitting capacitors and used a passive matrix addressing method. In this report, we cover the results of two proposal periods: September 2015 - August 2016 and September 2016 - July 2017.

Accomplishments: o We reported the first article on hyperelastic light emitting capacitors (HLEC), resulting in a display with the largest reported strain to failure (~500% linear strain). The HLEC may actually fail at higher strains, the display stopped working at 500% strain due to experimental limitations. (Fig. 1-3).

o We reported the first color changing soft robot that is electrically controlled. This soft robot is composed of silicone elastomer and the display is laminated onto its skin, which deforms by 100's% strain. (Fig. 4).

o We used the HLECs to not only display color on the soft robots, but also sense touch and for feedback control of the crawling soft robot. (Fig. 4).

o We developed a photolithography and transfer printing method to scale up the pixel density of the HLEC display and build a passive matrix controller to display individual pixel light emission. (Fig. 5-7).

o The high density HLEC array also serves as a multi-point touch sensor. (Fig. 8).

o While discussing collaboration with Dr. Roger Hanlon, it became evident that the ability to control the polarization of reflected light is important to study cuttlefish vision and, commensurately, camouflage. In order to control the polarization of our HLECs, it would require a stretchable polarizer layered onto the system; an added

complexity in fabrication.

o We reported a paper on Untethered Stretchable Displays for Haptic Interaction. This display is powered by batteries, changes shape from a flat disk to spherical orb, and senses touch while emitting light. (Fig. 9-14).

o We reported the first use of machine learning to interpret mechanical deformation as gestures. We pressurized a 5x5 grid of stretchable capacitors into a hemisphere and used it as a haptic interface. By classifying different the hemisphere deformations, we were able to train gestures to control a game of Tetris. (Fig. 15-18).

o Two students (Bryan Peele & Chris Larson) successfully defended their theses and graduated.

Training Opportunities: Several students received training through this program:
" Chris Larson (PhD candidate)
" Bryan Peele (PhD candidate)
" Shuo Li (PhD candidate)
" Jason Cortell (Staff)
Of these, Chris Larson and Bryan Peele have received their PhD and Shuo Li is close.

Results Dissemination: " Larson C, Peele B, Li S, Robinson S, Totaro M, Beccai L, Mazzolai B, Shepherd R. Highly stretchable electroluminescent skin for optical signaling and tactile sensing. Science (2016).
" Li S, Peele B, Larson C, Zhao H, Shepherd R. A stretchable multicolor display and touch interface using photopatterning and transfer printing. Adv. Mat. (2017).
" Peele B, Li S, Larson C, Cortell J, Habtour H, Shepherd R. Untethered stretchable displays for tactile interaction. Soft Robotics (accepted).
" Larson C, Spjut J, Knepper R, Shepherd R. A Deformable Interface that Learns Touch Gestures using Deep Neural Networks. Published on arXiv (https://arxiv.org/abs/1706.02542).
" Li S, Zhao H, Shepherd R. Flexible and stretchable sensors for fluidic elastomer actuated soft robots. MRS Bulletin (2017).

Honors and Awards: "PI Shepherd received ONR Young Investigator Award during this time period.
" Publication in Science magazine

Protocol Activity Status:

Technology Transfer: o Provisional patent applications:
o 62/250,172: Stretchable Electroluminescent Devices and Methods Making and Using Same; Photolithography procedure for mm2 area HLEC pixels patterned into RGB arrangements using transfer printing
o 62/317,834: Ultra-Stretchable Electroluminescent Device; Ionic hydrogel capacitors with embedded light emitting semiconducting particles in the dielectric layer.

PARTICIPANTS:

Participant Type: Graduate Student (research assistant)
Participant: Chris Larson
Person Months Worked: 12.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Shuo Li
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:

National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Bryan Nathan Peele
Person Months Worked: 12.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

DISSERTATIONS:

Publication Type: Thesis or Dissertation
Institution: Cornell University
Date Received: 28-Dec-2017 Completion Date: 5/5/17 5:36PM
Title: Deformable Media for Visual and Tactile Interfaces
Authors: Christopher Larson
Acknowledged Federal Support: **Y**

Publication Type: Thesis or Dissertation
Institution: Cornell University
Date Received: 28-Dec-2017 Completion Date: 12/18/17 6:00AM
Title: IMPARTING DEXTERITY, TOUCH, AND VISUAL EXPRESSION IN SOFT ROBOTICS
Authors: Bryan Peele
Acknowledged Federal Support: **Y**

WEBSITES:

URL: http://orl.mae.cornell.edu
Date Received: 28-Dec-2017
Title: Organic Robotics Laboratory
Description: Website of PI, Robert Shepherd, Assistant Professor at Cornell University

Stretchable Capacitors That Electrically Luminesce, Sense, and Actuate for Biomimetic Coloration, Shepherd, Cornell University

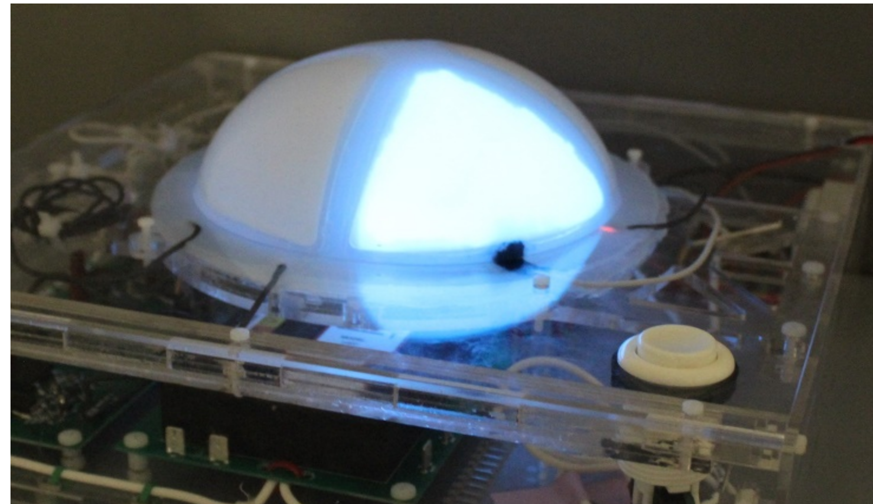
Objective: Develop a platform to accurately mimic cephalopod skin for dynamic coloration and posture to study visual perception in cuttlefish.

Scientific Challenges.

•Can we pattern high resolution light emitting dielectric elastomer actuators (which we call HLECs).

• Can we control them effectively?

• Can we use their sensing capabilities for shape control of soft robots and haptic interfaces?



Peele et al., Soft Robotics (accepted)

Major Accomplishments:

•Photolithography procedure for high density RGB HLEC pixels. Li et al., **Adv. Mat.** (2016)

•Applied HLECs to posture changing soft robot for dynamic coloration. Larson et al., **Science** (2016).

•Portable system for use in experiment with cuttlefish. Peele et al., **SoRo** (accepted)

•Review on stretchable sensors. Li et al., **MRS Bulletin** (2017)

•Machine learning interpretation of touch in high density stretchable sensor networks. Larson et al. IJRR (submitted)

•Stretchable Transducers for Kinesthetic Interactions in Virtual Reality (SIGGRAPH conference presentation; collaboration with NVIDIA Research).

Potential Army Relevance:

•Stretchable displays for visually indicating locations for transport, targets. A small display can turn into a large one for portability.

•Wearable dynamic coloration via counter illumination for daytime camouflage. (may require significant further development).

•Stretchable camouflage netting for equipment.

•Damage sensing via passive matrix sensor array.

•Haptic interfaces & displays for vehicles

R Shepherd: rfs247@cornell.edu; 607 255 8654

- Project Summary - Grant # W911NF-12-R-0011-2

(Final Report: September 2015 – July 2017)

Stretchable capacitors that electrically luminesce, sense, and actuate for biomimetic coloration

Robert Shepherd
Mechanical & Aerospace Engineering
Cornell University, Ithaca, NY, 14853

Objective

This proposal is about enabling methods to better understand visual perception as it pertains to dynamic camouflage. Cephalopod's (e.g., octopuses and cuttlefish) make themselves invisible to extremely sophisticated visual predation using dynamic camouflage. Despite their remarkable abilities, these animals use only three types of coloration patterns: Uniform, Mottled, and Disruptive. Overlaid on this color camouflage are many other disguise techniques; the cuttlefish, for example, also uses pattern generation, skin texture, and body posture to disguise or reveal themselves. Though some basic explanations of how these animals perform these maneuvers and when they choose to implement them has recently been explained, true understanding of how to control and use dynamic camouflage in a human context will only be revealed using synthetic systems, instead of animal models. The goal of this proposal is to develop synthetic chromatophores that display color electrically. To create stretchable synthetic chromatophores, we synthesized high density arrays of individually addressable elastomeric light emitting capacitors and used a passive matrix addressing method. In this report, we cover the results of two proposal periods: September 2015 – August 2016 and September 2016 – July 2017.

Section I (September 2015 – August 2016):

Objective

This proposal is about enabling methods to better understand visual perception as it pertains to dynamic camouflage. Cephalopod's (e.g., octopuses and cuttlefish) make themselves invisible to extremely sophisticated visual predation using dynamic camouflage. Despite their remarkable abilities, these animals use only three types of coloration patterns: Uniform, Mottled, and Disruptive. Overlaid on this color camouflage are many other disguise techniques; the cuttlefish, for example, also uses pattern generation, skin texture, and body posture to disguise or reveal themselves. Though some basic explanations of how these animals perform these maneuvers and when they choose to implement them has recently been explained, true understanding of how to control and use dynamic camouflage in a human context will only be revealed using synthetic systems, instead of animal models. The goal of this proposal is to develop synthetic chromatophores that display color electrically. To create stretchable synthetic chromatophores, we synthesized high density arrays of individually addressable elastomeric light emitting capacitors and used a passive matrix addressing method. **Importantly, we also discovered an entirely new method for achieving stretchable displays based on a new technology we developed based on elastomeric optical waveguides**.

Approach

- Synthesize highly extensible, transparent conductors and insulators that can be photopatterned at high resolution.

- Use microfabrication techniques to pattern hyperelastic light emitting capacitors (HLECs) that increase in size and emit light with applied voltage.

- Explore the trade-offs between increasing HLEC density and maintaining control authority over each synthetic chromophore.

- Explore the HLECs capabilities as tactile sensors. Application of these skins to soft machines will not only allow them to change color, but also afford closed-loop control over posture.

Relevance to Army

Tough, stretchable display technology is important for many reasons: (i) by conformally wrapping around any object, they can bring attention to or hide sensitive equipment, vehicles, or personnel; (ii) by undergoing large area changes, the displays can be portable yet stretched into large and more visible displays or active camouflage; (iii) it provides a technological pathway towards understanding how cephalopods use their posture, skin texture, and coloration for camouflage and display.

Accomplishments for Reporting Period

- We reported **the first article on hyperelastic light emitting capacitors (HLEC), resulting in a display with the largest reported strain to failure (~500% linear strain)**. The HLEC may actually fail at higher strains, the display stopped working at 500% strain due to experimental limitations. (**Fig. 1-3**).

- We reported **the first color changing soft robot that is electrically controlled**. This soft robot is composed of silicone elastomer and the display is laminated onto its skin, which deforms by 100's% strain. (**Fig. 4**).

- We used the HLECs to not only display color on the soft robots, but also **sense touch** and for feedback control of the crawling soft robot. (**Fig. 4**).

- We developed a photolithography and transfer printing method to scale up the pixel density of the HLEC display and build a passive matrix controller to display individual pixel light emission. (**Fig. 5-7**).

- The high density HLEC array also serves as a multi-point touch sensor. (**Fig. 8**).

- While discussing collaboration with Dr. Roger Hanlon, it became evident that the ability to control the polarization of reflected light is important to study cuttlefish vision and,

commensurately, camouflage. In order to control the polarization of our HLECs, it would require a stretchable polarizer layered onto the system; an added complexity in fabrication.

Collaborations and Technology Transfer

- Provisional patent applications:
  - 62/250,172: Stretchable Electroluminescent Devices and Methods Making and Using Same; Photolithography procedure for mm^2 area HLEC pixels patterned into RGB arrangements using transfer printing
  - 62/317,834: Ultra-Stretchable Electroluminescent Device; Ionic hydrogel capacitors with embedded light emitting semiconducting particles in the dielectric layer.

- Portable system developed for use in experiment with cuttlefish. Peele et al., IEEE RAM (in preparation). Samples sent to Dr. Habtour for dynamic mechanical analysis, results to be included in research paper.

- Talk at ARL, invite by Dr. Slipher. Continuing collaboration on variable compliance wings and stretchable displays.

- Established a collaboration with Dr. Roger Hanlon to determine feasibility of stretchable optical lightguides for studying vision in cuttlefish.

- I Corps grant submitted (08/31/2016) for integrating stretchable displays into haptic feedback gloves for rehabilitation and gaming using augmented and virtual reality.

Resulting Journal Publications During Reporting Period

- Larson C, Peele B, Li S, Robinson S, Totaro M, Beccai L, Mazzolai B, Shepherd R. Highly stretchable electroluminescent skin for optical signaling and tactile sensing. *Science* (2016).

- Li S, Peele B, Larson C, Zhao H, Shepherd R. A stretchable multicolor display and touch interface using photopatterning and transfer printing. *Adv. Mat.* (2017).

Graduate Students Involved During Reporting Period

- Chris Larson (PhD candidate)
- Bryan Peele (PhD candidate)
- Shuo Li (PhD candidate)
- Jason Cortell (Staff)

Awards, Honors and Appointments

- PI Shepherd selected to attend the National Academy of Engineering's United States Frontiers of Engineering meeting, 2016.

Section II (September 2016 – July 2017):

Objective

This proposal is about enabling methods to better understand visual perception as it pertains to dynamic camouflage. Cephalopod's (e.g., octopuses and cuttlefish) make themselves invisible to extremely sophisticated visual predation using dynamic camouflage. Despite their remarkable abilities, these animals use only three types of coloration patterns: Uniform, Mottled, and Disruptive. Overlaid on this color camouflage are many other disguise techniques; the cuttlefish, for example, also uses pattern generation, skin texture, and body posture to disguise or reveal themselves. Though some basic explanations of how these animals perform these maneuvers and when they choose to implement them has recently been explained, true understanding of how to control and use dynamic camouflage in a human context will only be revealed using synthetic systems, instead of animal models. The goal of this proposal is to develop synthetic chromatophores that display color electrically. To create stretchable synthetic chromatophores, we synthesized high density arrays of individually addressable elastomeric light emitting capacitors and used a passive matrix addressing method. **In this proposal period, we created a portable power system to operate the synthetic chromatophores (called HLECs), as well as use them as touch sensors. We applied this system to a spherical haptic interface that simulates the game Simon®. Further, we extended this concept to a high density spherical sensor surface for recognizing gesture via convolutional neural networks (CNNs).**

Approach

- Mold a circular array of HLECs, each emitting light at different frequencies.
- Use small high voltage amplifiers and high voltage relies in a compact form, powered by LiPo batteries to power the circular HLEC array.
- Integrate an air pump into the portable system to actuate the haptic interface.
- Feed the high density sensor array into a machine learning algorithm to interpret haptic input for computer control.

Relevance to Army

Tough, stretchable display technology is important for many reasons: (i) by conformally wrapping around any object, they can bring attention to or hide sensitive equipment, vehicles, or personnel; (ii) by undergoing large area changes, the displays can be portable yet stretched into large and more visible displays or active camouflage; (iii) it provides a technological pathway towards understanding how cephalopods use their posture, skin texture, and coloration for camouflage and display; (iv) by interpreting their deformation, these skins can be used for wearable sensor networks for health monitoring and non-verbal communication.

Accomplishments for Reporting Period

- We reported **a paper on Untethered Stretchable Displays for Haptic Interaction**. This display is powered by batteries, changes shape from a flat disk to spherical orb, and senses touch while emitting light. (**Fig. 9-14**).

- We reported **the first use of machine learning to interpret mechanical deformation as gestures**. We pressurized a 5x5 grid of stretchable capacitors into a hemisphere and used it as a haptic interface. By classifying different the hemisphere deformations, we were able to train gestures to control a game of Tetris. (**Fig. 15-18**).

- Two students (Bryan Peele & Chris Larson) successfully defended their theses and graduated.

Collaborations and Technology Transfer

- Dr. Habtour performed FEA to predict what pressures are required to achieve particular hemispherical shapes of the inflated HLEC array (paper in review).

- Talk at ARL, invite by Dr. Walsh, to discuss new ideas for powering robots (e.g., Robot Blood and Cannibalistic Skeletal Frames.

- The discussion we started with Roger Hanlon in this grant resulted in a paper published from another grant on texture camouflage (Science).

- We received an I Corps grant to explore commercialization of this and related technology (paper from that grant submitted to IEEE).

- Began a collaboration with NVIDIA Research for using their Jetson micro AI computing device for gesture interpretation (paper in review).

Resulting Journal Publications During Reporting Period

- Peele B, Li S, Larson C, Cortell J, Habtour H, Shepherd R. Untethered stretchable displays for tactile interaction. *Soft Robotics* (accepted).
- Larson C, Spjut J, Knepper R, Shepherd R. A Deformable Interface that Learns Touch Gestures using Deep Neural Networks. Published on arXiv (https://arxiv.org/abs/1706.02542).
- Li S, Zhao H, Shepherd R. Flexible and stretchable sensors for fluidic elastomer actuated soft robots. *MRS Bulletin* (2017).

Graduate Students Involved During Reporting Period

- Chris Larson (PhD candidate)
- Bryan Peele (PhD candidate)
- Shuo Li (PhD candidate)

Awards, Honors and Appointments

- PI Shepherd received ONR Young Investigator Award during this time period.

Figures (Section I)

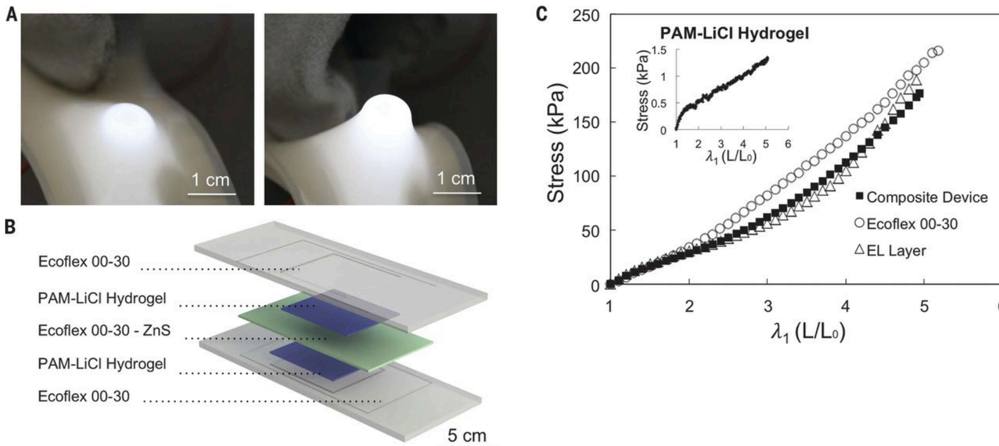


Fig. 1.
Hyperelastic light emitting capacitor (HLEC). (A) Image of the HLEC conforming to the end of a pencil. **(B)** Exploded view of the HLEC showing its five-layer structure consisting of a ~1 mm thick electroluminescent layer (ZnS-Ecoflex 00-30) that is sandwiched between two PAM-LiCl hydrogel electrodes and encapsulated in Ecoflex 00-30. **(C)** Stress-stretch curves of Ecoflex 00-30, the electroluminescent layer, the hydrogel, and the composite device.

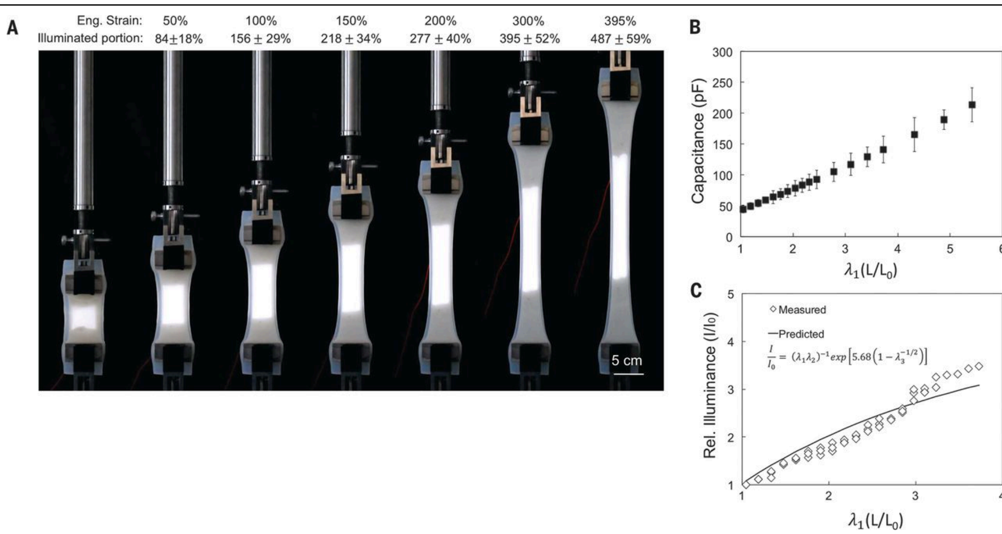


Fig. 2. The capacitive and luminescent behavior of the HLEC display under uniaxial stretching. (A) A nominal electric field of ~25 kV cm^{-1} was applied to the HLEC at the start of the uniaxial test. Five lengths were measured using Image-J to obtain λ_1 across the width of the illuminated portion of the tensile bar. We report the mean and standard deviation of those measurements. At an engineering strain (grip-to-grip) of 395%, we measured the mean strain of the illuminated portion to be 487%, with a range of 420 - 549%. **(B)** The capacitance of the HLEC as a function of its uniaxial stretch (n = 4). **(C)** The relative illuminance of the HLEC versus its uniaxial stretch (n = 4) plotted alongside predicted values (supplementary online text).

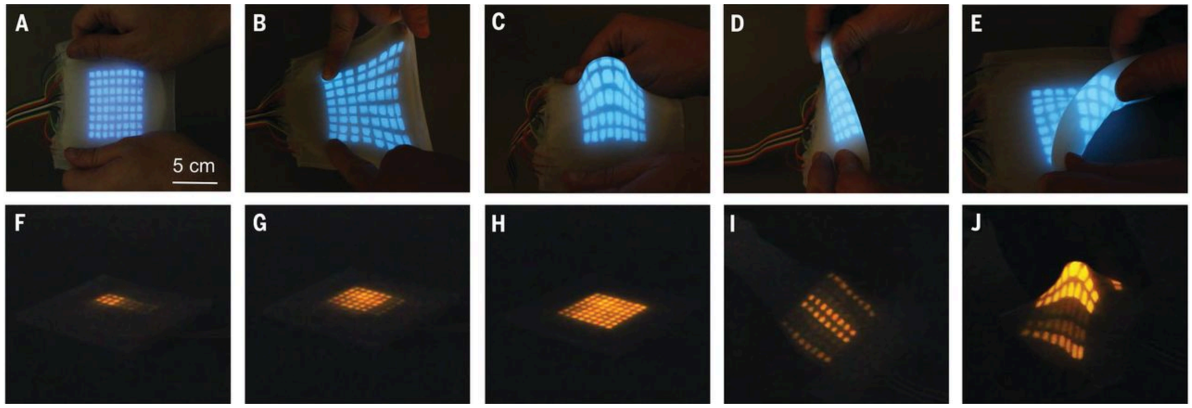


Fig. 3. Multi-pixel electroluminescent displays fabricated via replica molding. The device measures 5 mm thick, with each of the 64 pixels measuring 4 mm. We show the devices in various states of deformation and illumination: **(A)** undeformed, **(B)** stretched, **(C)** conformed to a finger, **(D)** folded, **(E)** rolled, **(F-H)** subsets of pixels activated, and **(I-J)** subsets of pixels activated while being deformed.

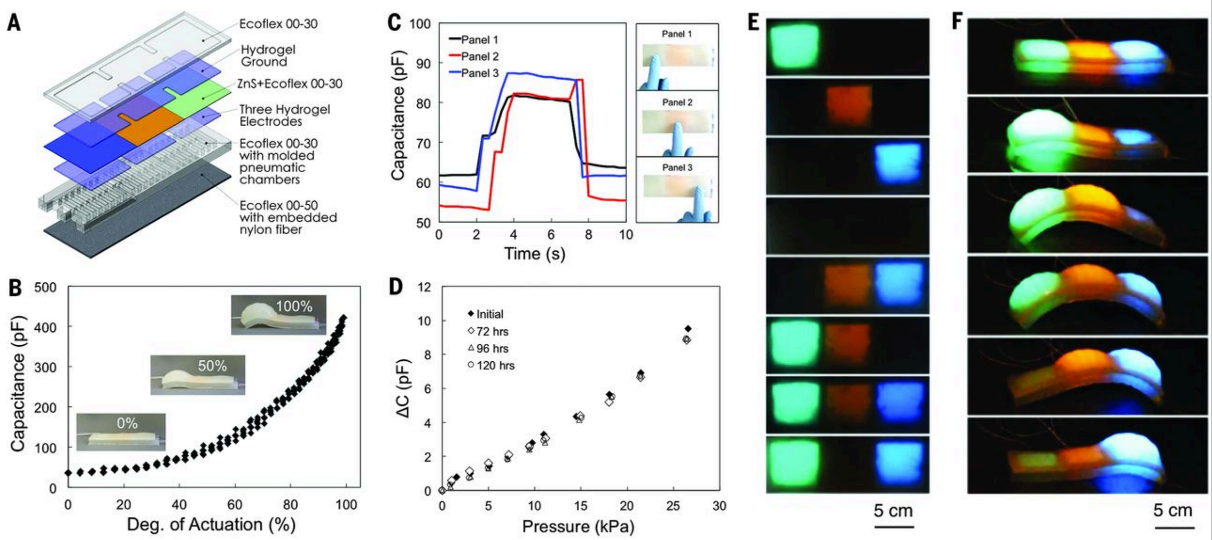


Fig. 4. HLEC skins endow soft robots with the ability to sense their actuated state, environment, and communicate optically. (A) Schematic of a three-chambered fluidically actuated crawler. A series of three independently actuated pneumatic chambers are embedded between the HLEC skin (top) and a strain limiting layer (bottom). **(B)** Capacitance plotted versus the actuation amplitude, which we define as the relative change in deflection between the uninflated and fully inflated states (n = 5). **(C)** A firm finger press induces a ~25% increase in capacitance. **(D)** Change in capacitance versus applied pressure. We observe a negligible change in the capacitive response of the sensors over a period of 120 hours. **(E)** Array of three HLEC panels, each emitting a different wavelength through selective doping of the EL phosphor layer. Each HLEC panel is activated independently. **(F)** An undulating gait is produced by pressurizing the chambers in sequence along the length of the crawler. As each pneumatic chamber is pressurized, the outer electroluminescent skin is stretched, increasing the electric field across the EL layer and thus the luminescence.

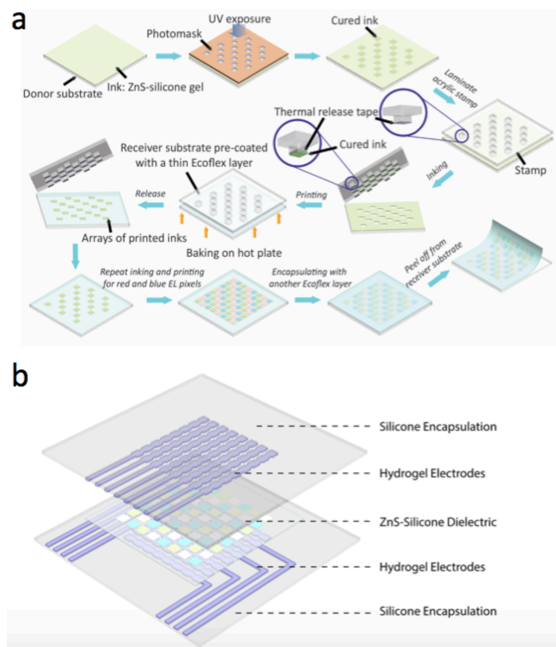


Fig. 5. (a) Schematic illustration of the process flow for photopatterning and transfer printing to form the multicolor electroluminescent dielectric layer. (b) Exploded view of the m-HLEC showing its five layers comprising a ~1.3 mm thick EL dielectric layer (ZnS-silicone) that is sandwiched between top and bottom hydrogel electrodes in orthogonal layouts and protected by a silicone encapsulation layer.

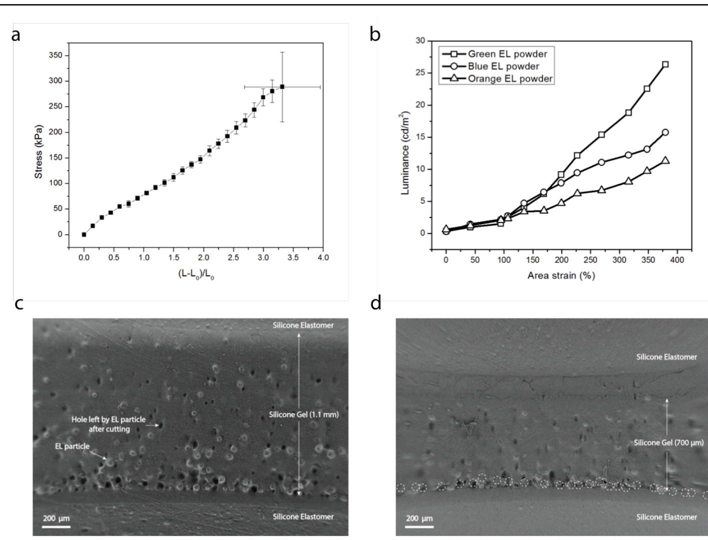


Fig. 6. (a) Stress-strain curve of the ZnS-silicone gel-silicone elastomer composite light-emitting dielectric layer. The nominal stress, σ, is defined as the force applied on the dog-bone shaped composite, divided by the cross-sectional area of the undeformed middle section. (b) Luminance of m-HLEC fabricated using three different colored EL phosphor powders in response to area strains. (c) Cross-sectional scanning electron microscopy (SEM) image showing the distribution and morphology of EL particles embedded in silicone gel matrix and encased in silicone elastomer encapsulation for an unstrained sample. (d) Cross-sectional SEM image for a uniaxially strained sample. White dotted circles represent the locations of EL particles in the unstrained state.

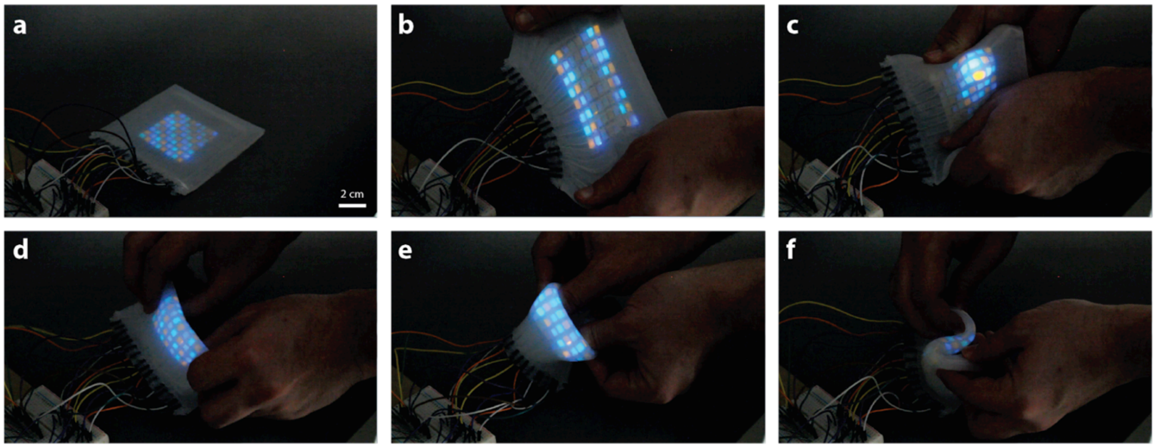


Fig. 7: **m-HLEC showing dynamic patterns under various deformations**. (a) Illuminating all pixels, undeformed; (b) illuminating left and right four columns, stretching; (c) illuminating top right corner 5×5 pixels, wrapping around a finger; (d) illuminating all pixels, folding; (e) illuminating middle six columns, rolling; (f) illuminating center 4×4 pixels, twisting.

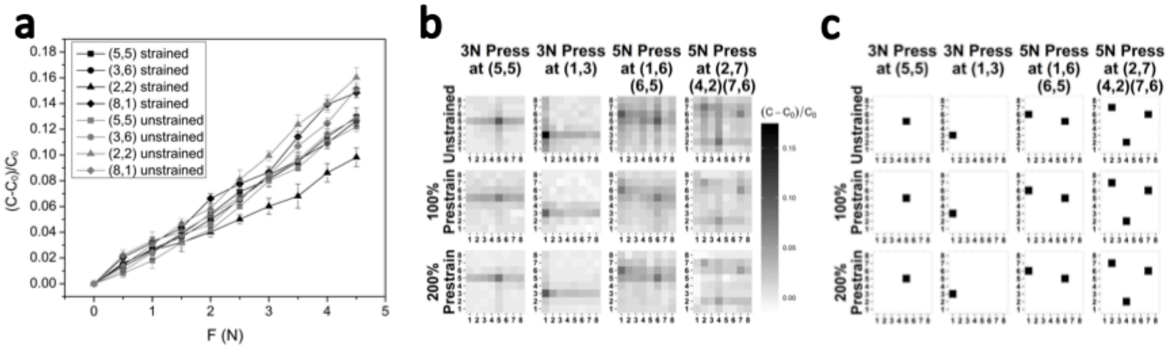


Fig. 8: **Touch sensing capability of the m-HLEC**. (a) Normalized relative capacitance in response to applied force at four randomly selected pixels in the range of 0-4.5 N, for both unstrained and strained (ε_{area}=100%) states. (b) Greyscale gradient in the topographical map demonstrates normalized relative capacitance in response to applied force at unstrained and strained (ε_{area}=100% and 200%) states. (c) Pixels shown in black have been identified as being pressed using a weighted filter that compares the normalized relative capacitance of each pixel to that of its neighbors.

Figures (Section II)

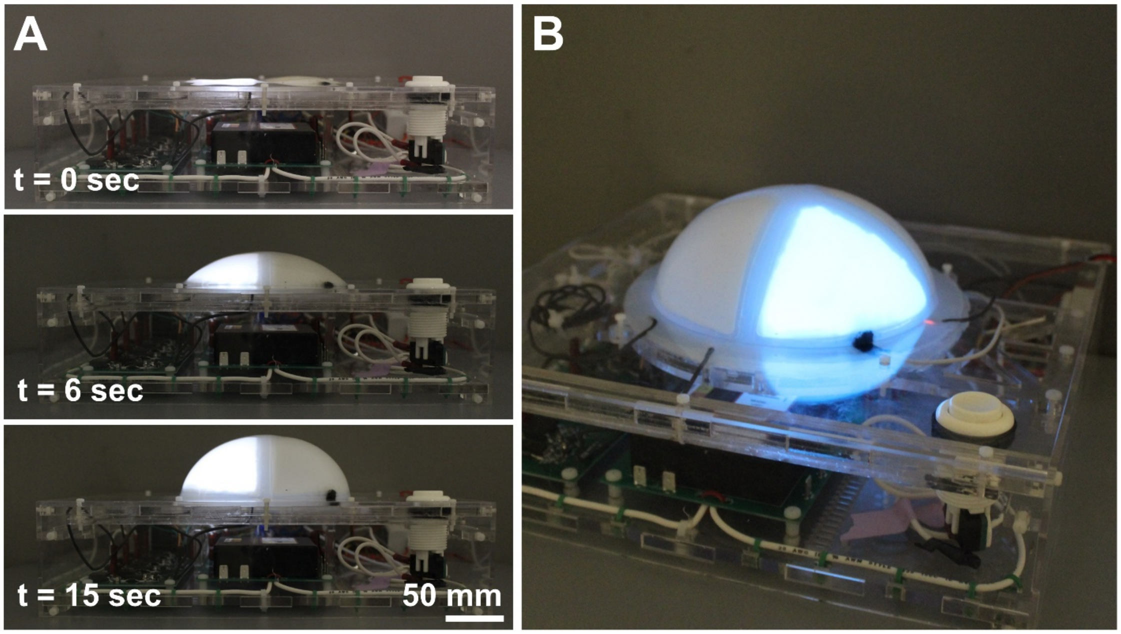


Fig. 9. **Four hyperelastic light-emitting capacitors (HLECs) form an untethered soft interface capable of emitting light and sensing touch.** (**A**) The membrane is pressurized using an integrated pump. (**B**) Fully inflated HLEC interface with one panel illuminated using applied voltage, $V \sim 4$ kV, and frequency, $f \sim 1$ kHz.

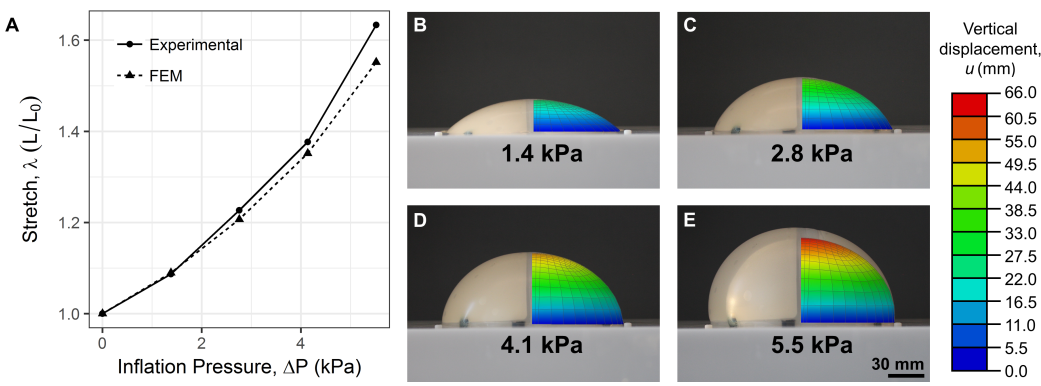


Fig. 10. Stretch of the elastomeric membrane during inflation. (**A**) Aggregate stretch across the profile of the HLEC membrane as internal pressure is applied. Experimental results are compared to results of a numerical simulation. Profiles of the device are shown alongside vertical displacement, *u*, for pressures of 1.4 kPa (**B**), 2.8 kPa (**C**), 4.1 kPa (**D**) and 5.5 kPa (**E**). Simulations performed by Dr. Habtour (ARL).

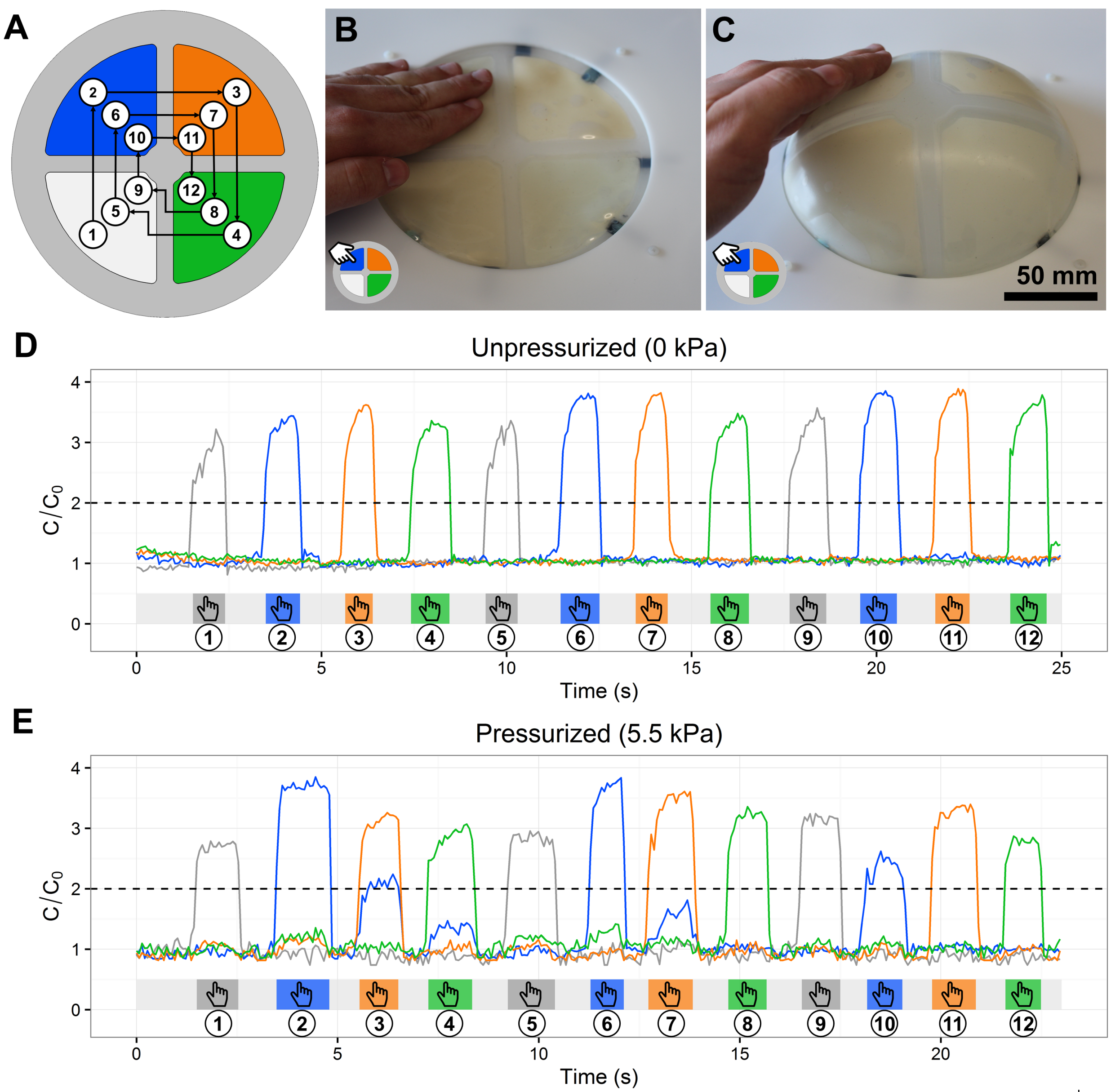


Fig. 12. Touch sensing capabilities of the HLEC panels. (**A**) Sequence of touches to the HLEC panels, starting with the white panel in the bottom left and proceeding clockwise around the device. A sequence of twelve touches (three per panel) is repeated for the unpressurized and pressurized states. (**B**) Representative touch on the blue panel in the unpressurized state. (**C**) Representative touch on the blue panel in the pressurized state. (**D**) Relative capacitance for each HLEC panel as they are pressed in the unpressurized state. (**E**) Relative capacitance for each HLEC panel as they are pressed in the pressurized state. The dashed grey lines in **(D)** and **(E)** indicate the threshold used to indicate whether a panel has been pressed. The colored rectangles below the capacitance data represent which panel, if any, have been identified as being pressed.

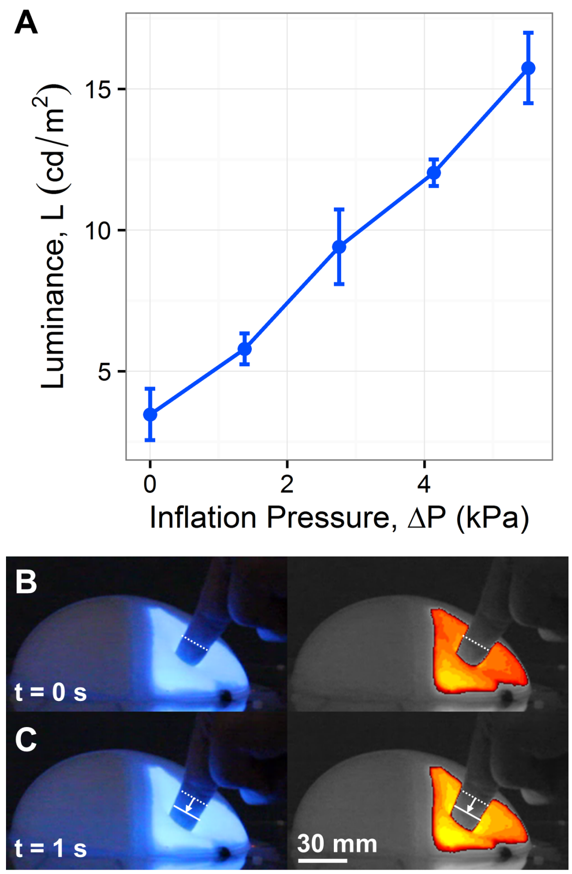


Fig. 13. Change in luminance during deformation. (**A**) Luminance for the blue panel as the membrane is pressurized. Error bars represent the standard error calculated using three measurements. (**B-C**) Pressurized HLEC panel being deformed with a finger press while illuminated. The images on the right show the relative luminance of the device, with yellow coloration corresponding to the highest luminance.

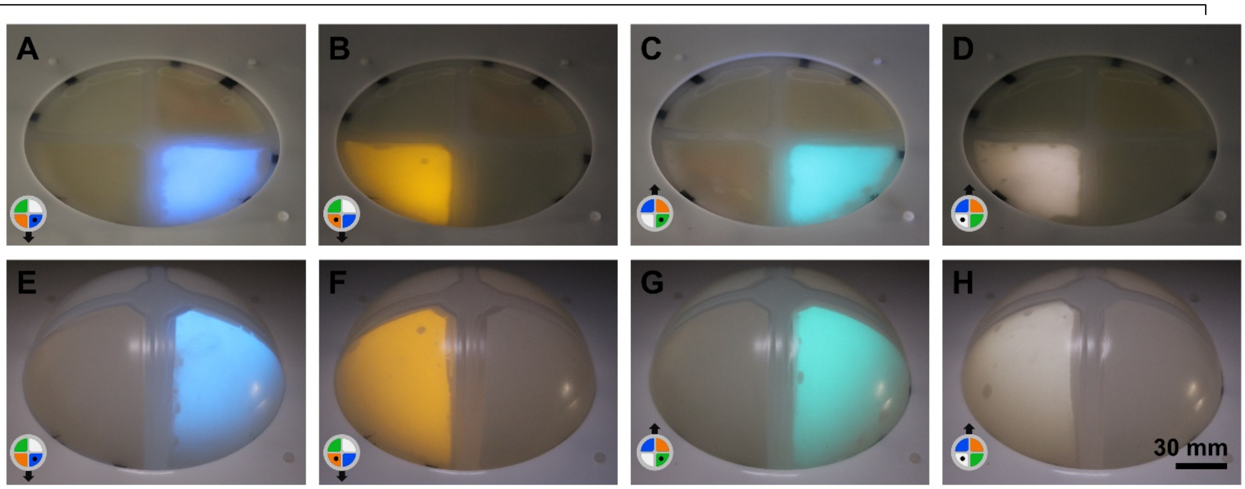


Fig. 14. Illumination of the HLEC panels. Blue (**A**), orange (**B**), green (**C**) and white (**D**) panels are illuminated while the membrane is uninflated. Blue (**E**), orange (**F**), green (**G**) and white (**H**) panels are illuminated while the membrane is pressurized to ~4.1 kPa.

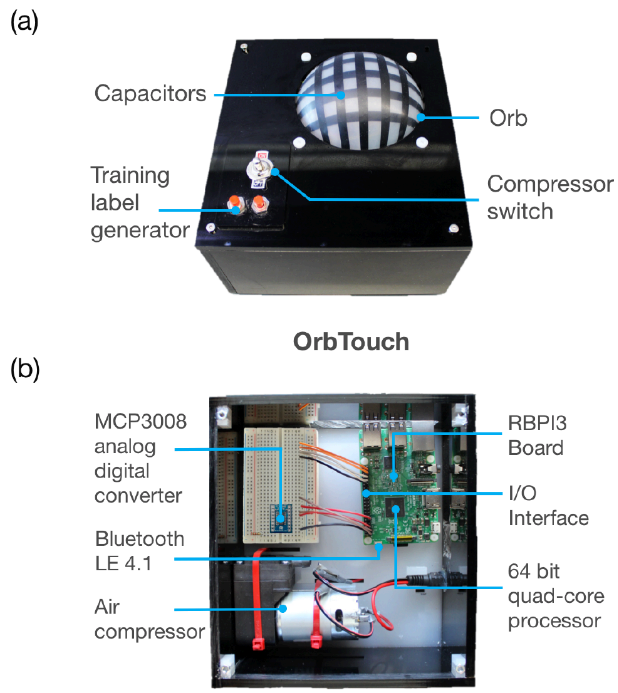


Fig. 15. Photographs of the OrbTouch device. (a) Its embedded capacitors capture shape changes caused by human touch. (b) The internal components of OrbTouch consist of an embedded RBPI3 computer, ADC, and air compressor used to control pressure in the orb.

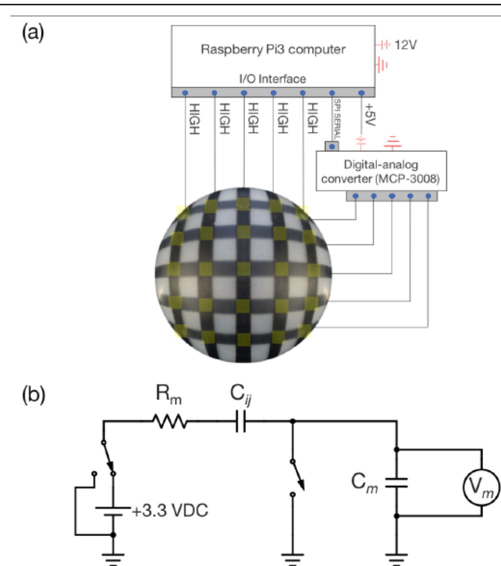


Fig. 16. Capacitance measurement method. (a) To measure capacitance, we set one vertical electrode HIGH (+3.3 VDC) and monitor the induced voltages on the orthogonal electrodes using an ADC, which relays the signals to the RBPI3 over SPI serial. During each measurement, there is one pin set HIGH, and one pin that is read; the remaining eight electrodes are connected to ground to minimize cross talk between neighboring electrodes and electromagnetic interference. (b) Equivalent measurement circuit. The i,j^{th} capacitor is represented by $C_{i,j}$. The nominal capacitance of our sensors is 41.2 pF (SD = 2.9 pF). We use a R_m = 50 Mohm inline resister to yield an RC time constant of τ~2 ms. We use a second capacitor, C_m = 1 pF, to flip the polarity of the measured V_m voltages.

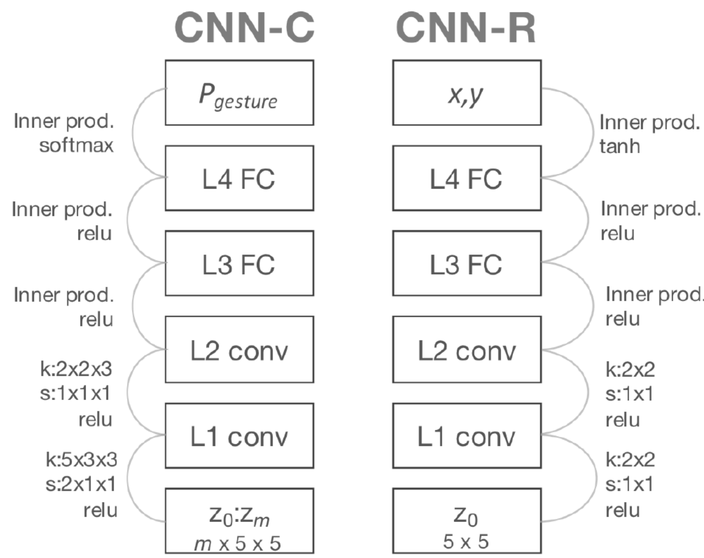


Fig. 17. Computational graph of the inference (CNN-3D) and regression (CNN-2D) models. Both networks have two hidden convolutional layers and two hidden fully connected layer. The kernel size, k, and stride, s, of each convolutional operation are provided. Network CNN-3D accepts as input a sliding window of m discrete sensor readings (5x5xm) and outputs a probability distribution over n_c classes using a softmax activation on the output. Because the information in a gesture is inherently spatiotemporal, we convolve a 3D kernel over both the spatial and temporal dimensions of the input to capture relevant features. Network CNN-2D accepts a 5x5 sensor matrix and outputs a continuous valued vector using a tanh activation on the output layer.

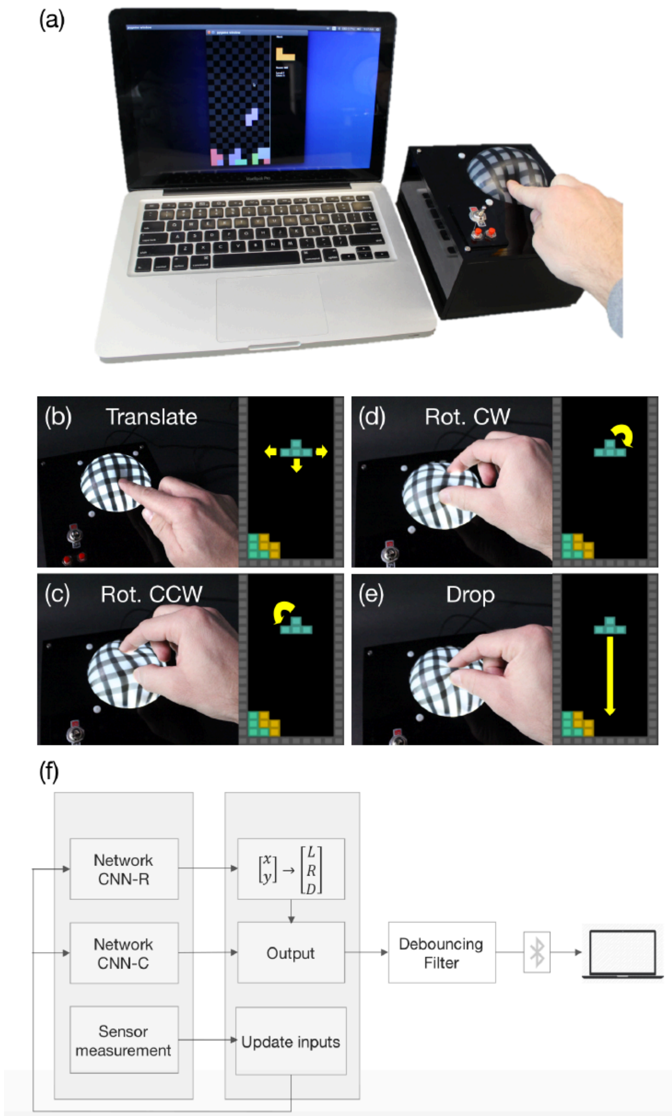


Figure 18. Application of OrbTouch to the popular game Tetris. (a) Photograph of OrbTouch being used to control an adaptation of the game Tetris. (b) Finger pressing, or poking are used to translate the Tetromino left, right, and down (L,R,D). (c) Pinching is used to drop the Tetromino directly to the bottom of the grid.(d) Clockwise rotation, or twisting, is used to rotate the Tetromino 90 deg in the clockwise direction. (e) Counterclockwise rotation is used to rotate the Tetromino 90 deg in the counterclockwise direction. (f) OrbTouch software diagram. The first processing step executes capacitance measurements, CNN-2D, and CNN-3D, while the second step generates a command and updates the model inputs for the next timestep. Each of these steps is multithreaded. We use debouncing filter prior to sending commands to the host (via Bluetooth). Each cycle of compute takes ~86 ms, which fits within our 100 ms target.